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Fuzzy Models of Intelligent Industrial Controllers and Control Systems. I. Organizational, Engineering, Cost, and Applied Aspects*

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The scientists of many countries are devoting increasing attention to research in the development of intelligent automatic control systems based on fuzzy models of controllers. The increasing demand for such systems for both industrial and domestic applications is emphasized, together with the increase in capital investment for research and development of experimental and commercial prototypes of such systems. Information on the engineering, cost, and organizational problems of developing models of fuzzy controllers and control systems are given together with specific examples of system design and implementation.

Key words: Fuzzy controllers; fuzzy logic; intelligent control systems.

INTRODUCTION

Interest in the applied aspects of automatic control theory has been on the decline over the last three decades, as revealed by the significant drop in the number of domestic publications in this field. The number of papers on automation hardware has dropped by greater than a factor of 5 and the number of papers on control systems has fallen by nearly a factor of 3 according to [1]. The purpose of this paper, which consists of four parts, is to partially fill this gap in the domestic literature, and to clarify the necessary aspects (from theoretical principles through marketing) of a new field in control theory: fuzzy models of intelligent controllers and control systems. In recent years (from 1980 to date) there have been efforts in parallel with traditional research to achieve practical applications of fuzzy controllers, control systems, and expert systems in both the industrial and nonindustrial spheres [2]. The experts [3–11] believe that Japanese companies have assigned priority to the practical commercial application of fuzzy control models. To date, there are more than 400 practical applications of fuzzy controllers and control systems [12]. Capital investment in research and development of commercial prototypes in this field are distributed as follows (in billions of US dollars) [13]: Japan—2, USA—0.2, Europe—0.3 for 1990; Japan—2, USA—0.8, Europe—1 for 1995; and Japan—6, USA—3, and Europe—7 for the year 2000. Such accelerated development and corresponding material costs have been based on careful planning and extensive marketing (including testing at four international symposiums from 1987 through 1991 and an analysis of the organizational aspects of commercial designs). These processes were preceded by an extended period (1970 through 1980) of research to develop methods of analysis, synthesis, modeling, and design for producing optimal models of fuzzy controllers and control systems [2, 3, 14–26].

All concepts and definitions of fuzzy models of controllers and control systems used in this paper are described in detail in [14–17, 20] and, to the extent necessary, will be cited in appropriate positions in the text.

The material in this paper is organized as follows. Basic information on the engineering, cost, and organizational problems of developing models of fuzzy controllers and control systems are given in the first section, together with specific examples of designs and implementations of such systems. The second section is devoted to a description of the features of the design and dynamic analysis of knowledge-based structures of intelligent control systems. The third section contains

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an analysis of specific designs of intelligent fuzzy controllers together with a description of their applications in various problem-oriented areas. This section also discusses the problems of hardware and software and the construction of commercial fuzzy controller design systems. A description of fuzzy control and expert system designs for both commercial and noncommercial applications together with future directions in the design of fuzzy intelligent control systems is given in the fourth section of this paper.

1. Applied Aspects of Organizational, Engineering, and Cost Questions of Developing Fuzzy Control Systems

The first results (1975) from modeling the dynamic behavior of a fuzzy controller [17, 27] and the introduction in 1980 of the first fuzzy control system at a cement factory in Denmark [28, 29] (the fuzzy control system was based on simulating the behavior of a human operator controlling a furnace 5 m in diameter and 165 m in length for producing cement from limestone and silica, designed by F.L. Smidth) demonstrated the high efficiency of fuzzy controllers and control systems in controlling complex nonlinear dynamic systems. Among the most obvious applications of fuzzy controller and control system models was the metropolitan train traffic management system on the Nanboku line in the city of Sandi (220 km north of Tokyo; Prefecture of Miyagi, Japan) installed in June 1987. The line was 13.6 km long and interconnected 16 stations. The previous control system, which was based on PID controllers, did not yield the required stopping accuracy or travel comfort during train departure or braking. The new fuzzy control system guarantees a train stop accuracy of better than 7 cm from a prescribed point, a high degree of travel comfort, and a decrease in power costs by up to 35%. Another example is the water purification chlorination process control and monitoring system used in the municipal water supply system of the city of Sagamihara (Prefecture of Kanakawa, Japan). The fuzzy controller uses 47 linguistic logic reasoning rules, of which 15 apply directly to the selection of the quantity of chlorine additives for the biochemical water purification process, while the remaining 32 rules take into account the seasonal conditions of the year and environmental effects. The fuzzy controller runs a test every 5 minutes in place of an essentially nonlinear control system. High efficiency of fuzzy controllers is achieved in the collective control of freight elevators in high-rise buildings. Mitsubishi Electric Corporation has developed a fuzzy control system for single and multiple elevators that makes it possible to reduce a 1 min elevator waiting time by 15–20% and a waiting time of more than 1 min by 30–40%. A number of other examples can be found in [2–8, 18, 24, 25] and in Section 4 of this paper.

It should be noted that to date there have been approximately 200 actual models of fuzzy controllers and intelligent control systems employing expert systems that have found practical applications to date. It is worthwhile in this respect to note the comment by the well-known specialist in this field, M. Sugeno [4]. There are more than 2000 expert system design projects currently being pursued in Japan. Of these, only 20–40% have been successful in practice. In turn, 80 of 100 expert fuzzy system designs have found practical application, wherein 90% of these 80 designs are used in engineering practice and the remaining are used in the nonindustrial sphere. The latter include the thyroid cancer image diagnostic system developed at Kawasaki Medical School [30]. The experimental testing of this expert system has revealed that the diagnostic accuracy in analyzing thyroid cancers of internal organs has reached 92%, whereas experienced specialist physicians had a diagnostic accuracy on the same subjects of only 83%. Hybrid medical expert systems employing both a deep-level and a free knowledge representation format, and inductive logic reasoning for choosing prostheses and diagnosing the quality of prosthetics for the lower extremities of the disabled (the "Dasha" expert system) have been developed to date [31–33]. A new level of interest in fuzzy systems arose following model and full-scale experiments at the Johnson Space Center with an on-board Shuttle control system based on a fuzzy controller. The experimental results showed that the fuzzy control system is 25% more effective than a human operator and a standard PID-controller control system. As a result, in September 1987, the U.S. National Space Research Federation employed fuzzy controller technology for on-board spacecraft control systems. The basic element of such a fuzzy controller is the fuzzy processor developed by Yamakawa and introduced into service by NASA for a 2-year period, followed by commercial production. Since 1990, fuzzy controllers have been widely used in such domestic equipment as vacuum cleaners, washing machines, air-cooled oil cookers, domestic air conditioners, refrigerators, etc. [34].

These practical results attracted many researchers to this field. It is sufficient to note that there have been more than 5000 scientific papers (including 200 monographs) published on the theory and application of fuzzy systems. There are approximately 3000 specialists in China and approximately 500 researchers operating in each of the following countries:

the U.S., India, Europe, and the CIS, while between 800 and 1000 researchers are working in Japan. In addition to national, European, and international associations of fuzzy systems researchers, there have been a number of major laboratories established that specialize in the development and application of commercial hardware and software products and tools for constructing fuzzy intelligence systems. These include Togai Infra Logic, Omron, Micro Devices, and the Japanese International LIFE Laboratory (the International FUZZY Engineering Research Laboratory), etc. [3, 4, 8–10, 13]. Togai Infra Logic (Irvine, California) is the first company to manufacture fuzzy logic chips. TIL-shell software, which includes an expansion of the ASSEMBLER and C languages for the first digital fuzzy logic chip (the FC 110), is currently under development. Between 30 and 300 staff are currently employed at LIFE (Kanagawa Prefecture, city of Kanai, district of Yokohama) under the direction of T. Terano, in three 500-m^2 laboratories. The laboratory was founded in 1989 and is engaged in the development and commercial introduction of commercial fuzzy systems in three areas: fuzzy control systems (the Omron Research Group, Director: T. Yamakawa), fuzzy information processing (Matsushita, Director: T. Takagi), and fuzzy computer systems (Hitachi, Director: S. Yasunobu). The laboratory staff consists of temporary group A staff members (with annual contracts and a budget of 8.9 million dollars) and group B staff members (permanent staff members, with an annual budget of 3.4 million dollars). The laboratory was formed by a consortium of 48 transnational companies and has a budget of 45 million dollars for a 5-year period. It is anticipated that by 1995 approximately 4.2 billion yen will be spent in Japan on the development of a commercial prototype of a fuzzy processor. Researchers are working under two programs (one within the framework of laboratory activities and the other developed at the instigation of one researcher) with a total scope of 130 man-years. The Omron company specializes in the development of fuzzy controllers and VSLI chips. In this connection, Yamakawa has developed two types of new analog chips for fuzzy processing: the first chip implements a compositional (min-max) Sade inference rule in hard-wired form, and the second chip converts the fuzzy control signal values into nonfuzzy numerical values (a "defuzzifier") by the center of gravity method. The experimental prototype fuzzy controller developed in 1987 is 100 times faster than traditional PID-controllers. Omron has spent 3.3 billion dollars on the production of industrial control systems employing fuzzy chips. Omron Tateitsi Electronics Company plans to manufacture products based on fuzzy processors and control systems valued at up to 100 billion yen (1.3 billion marks) in 1994; specifically, these include the FZ-3000 and FZ-5000 fuzzy controllers run on NEC-PC-9801 personal computers with a production rate of up to 40 fuzzy logic rules ranging from 400 to 5 ms. The FS-2000 software makes it possible to implement up to 40 logic rules per chip at an individual cost of 5200 marks. Also note that the FC110 fuzzy processor model by Togai can be used as a coprocessor with standard computers (personal computers) compatible with the FUZZYC compiler priced between 80 and 1000 dollars. A PC-compatible compiler costs 4950 dollars, whereas the cost of the SUN Apollo and Sony workstation versions is 9900 dollars. According to [8], Omron had acquired 6 patents from Yamakawa in 1984, and in 1988 had already developed experimental prototypes of fuzzy chips and controllers; in 1989, the company produced up to 10 different types of controllers, and 60 demonstration prototypes of fuzzy logic products were displayed at an Omron presentation. Six hundred fuzzy logic designs had been patented by 1990, and the number of patents rose to 700 in 1991 with 40 of these patents granted to independent devices with a fuzzy control system. The Office of Computers and Business Equipment published a survey [35] in 1992 describing 350 patents (including 319 belonging to Japanese companies) from 30 problem-oriented areas of application of fuzzy controllers. According to [11], 1080 fuzzy logic designs had been patented in Japan by the end of 1991: 347 patents were granted in 1990, and 533 patents were granted in 1991. The experts believe [3, 4, 7, 8, 36–40] that approximately 70% of all intelligent system designs in the near future will be based on fuzzy logic, and Omron specialists, in particular, believe that up to 30% of the intelligent control systems developed in Japan in the next 5 years will employ fuzzy controllers.

2. Hardware and Software and the Features of Designing Microprocessor Fuzzy Controllers

One possible method of solving the problem of increasing the effectiveness, mobility, and flexibility of control systems is to increase the "intelligence" of the computer-aided design systems, to reduce the level of complexity of the hardware and software of the controllers, and to develop integrated "intelligent" production capacities employing progressive technology [2, 15, 20–25]. A knowledge base utilizing a variety of search, knowledge extraction, and representation methods [41–44] is employed as the basis for designing intelligent controllers. Therefore, commercial fuzzy controllers are developed on the basis of the developing theory of artificial intelligence systems [20, 21, 23–25, 45]. These questions are examined in the second half of this study. Fuzzy controllers, which are generally knowledge based and are used in intelligent industrial computer-aided design systems, have a number of advantages over traditional P–, PI–, and PID controllers [2, 23–25, 46–50] as well as a number of limitations [51, 52].

A fuzzy processor is used as the basis of the hardware implementation of the intelligent control structure with a fuzzy controller as shown in Fig. 1 (from [2]). In these models, the degree of complexity of the structural implementation and of the hardware and software is reduced by employing internal special-purpose VLSIC microprocessor modules (as sixth generation fuzzy processor computer prototypes) employing specified fuzzy logic. Fuzzy logic controllers utilize the concepts of fuzzy logic: fuzzy implication and compositional logical reasoning models. The following linguistic description scheme is traditional for fuzzy controllers which utilize in their knowledge base a realization of the corresponding production fuzzy logic reasoning model based on a fuzzy processor: fuzzy implication; fuzzy modifiers; fuzzy logic relations; a composition reasoning rule, and statements for converting logical linguistic control descriptions into nonfuzzy numerical values (defuzzifiers). In this case it should be noted that it is difficult to achieve a real-time implementation of approximation reasoning in the form of "if, then" production rules with hundreds and thousands of fuzzy implications on traditional computer models. Hence the corresponding development of tools has been aimed at advancing and modernizing the component base of fuzzy processors as well as the structures of the processors themselves (both specialized fuzzy computers designed for independent use or as a standard personal computer coprocessor).

Fuzzy memories are required to process fuzzy linguistic data; such memories store fuzzy words (the membership function of a fuzzy set is sampled and represented as an n-element vector, which is called a fuzzy word) for multistep fuzzy reasoning. A binary flip-flop, which stores information bits, functions in a standard computer as the main component in the memories. A corresponding definition of a fuzzy flip-flop for fuzzy memories based on the concept of triangular norms (conorms) and fuzzy negation statements has been proposed in [53–55]. More general fuzzy reasoning models based on triangular norms [56] and fuzzy memories based on neural nets [57] have made it possible to improve the speed and total memory capacity of fuzzy processors considerably.

Specialized processor, fuzzy knowledge bases, and fuzzy reasoning structures have also been developed in several directions as hybrid fuzzy processor technologies. As noted in [3], the time required to process fuzzy logic reasoning from a set of 96 production rules (5 input variables and two output variables) on a standard PC XT/AT computer with a 16-bit 8086 processor was 30 s. Significantly greater speed is required for control systems to operate in real time.

The first digital fuzzy processor (the FC 110) based on a fuzzy logic reasoning chip is a high-efficiency coprocessor for real-time fuzzy logic reasoning and fuzzy control algorithms [58–61]. The FC 110 processor has 256 bytes of RAM per chip, a byte data format and a machine command set consisting of a limited number of complex instructions (an RISC-architecture modification). Special commands are input for estimating the left-hand and right-hand logic sections of the "if, then" fuzzy production rules, and likewise for generating complex composite rules. In this case, the FC 110 processor operating at 10 MHz has a rule processing speed of 35 μs, and a logic rule generation rate of 28,000/s (an 80386 processor operating at 20 MHz generates such rules in 400 μs and 2300 rules in 1 s). It is advisable to employ an FC 110 special processor as a fuzzy coprocessor in conjunction with the main general-purpose computer, when the main processor also performs all input and output conversions, while the FC 110 processor evaluates the status of the knowledge base [61]. The FC 1101CE symbolic internal emulator for the FC 110 processor was established to accelerate the development, adjustment, and debugging of applied intelligent fuzzy logic systems: specifically, for designing knowledge bases for expert systems [58, 59, 61]. An example of the effective application of an FC 110 processor is the use of such a processor in a fuzzy controller structure [61, 62] for the stable control of a reversible pendulum. The programming language for implementing the fuzzy knowledge base employing an FC 110 fuzzy processor was a modified fuzzy C language; a fuzzy μFPL programming language was also developed. The fuzzy C development system can also be combined with a TIL-shell to generate control programs utilizing knowledge bases formulated by means of the TIL-shell version. The FC 110 coprocessor can be used to process upward of 370,000 fuzzy production rules (in two packets) in 1 s, and more than 1 million Boolean production rules in 1 s based on an IBM PC AT personal computer. In particular, the Togai VME subsystem operates at the speed of four ATs, using four FC 110 chips in parallel [63, 64].

A high production rule processing speed is achieved by constructing a fuzzy processor in the form of analog VLSI chips (ranging from 1 to 10 million fuzzy logic rules per second). Two types of analog tools for fuzzy information processing, a fuzzy processor and a fuzzy controller, are described in [65, 66]. The FUZ-M1 fuzzy processor can process fuzzy information and initiate approximate reasoning in a time of 100 ns; a fuzzy controller (after inputting deterministic information) initiates a control procedure based on approximate reasoning. In this case, a VLSI circuit is used where one chip generates a fuzzy reasoning rule in the form of a generalized *modus potens* rule. We will consider the features of the design

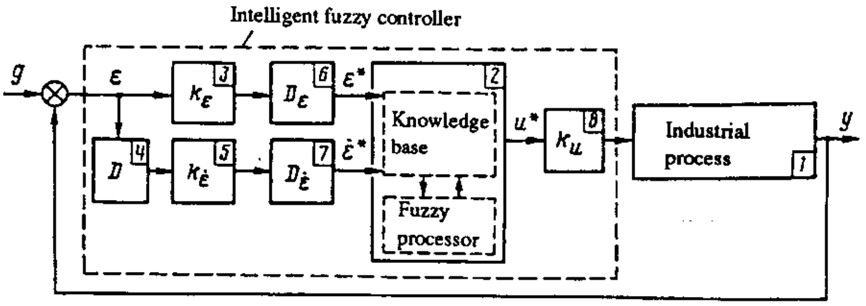


Fig. 1. Block diagram of an intelligent control system with a fuzzy controller.

of specific systems structures as shown in Fig. 1, in view of the importance of employing fuzzy processors in fuzzy controllers.

Example. Let us assume that it is necessary to implement a set of logic rules for a fuzzy control algorithm of the type "if x is *positively mean* (PM) and y is *approximately zero* (AZ*) and Z is *negative* (0), then C is *positively mean* (PM*)," etc.

A block diagram of a fuzzy logic circuit based on the center of gravity method is shown in Fig. 2a. A block diagram of the hardware implementation of a fuzzy processor utilizing logic fuzzy reasoning based on the center of gravity method is shown in Fig. 2b [65, 66]. Here, the input signal of the labels (X, Y, Z) can be implemented as U- and V-membership functions, and the logic result can be implemented by 25 logic elements. The values of the AZ and PA denote that the membership function is realized for these values in U form, while the remaining are implemented in V form. The use of such a fuzzy controller for the stabilization control of a reversible pendulum has also demonstrated high efficiency compared to traditional control methods employing a PID controller [67].

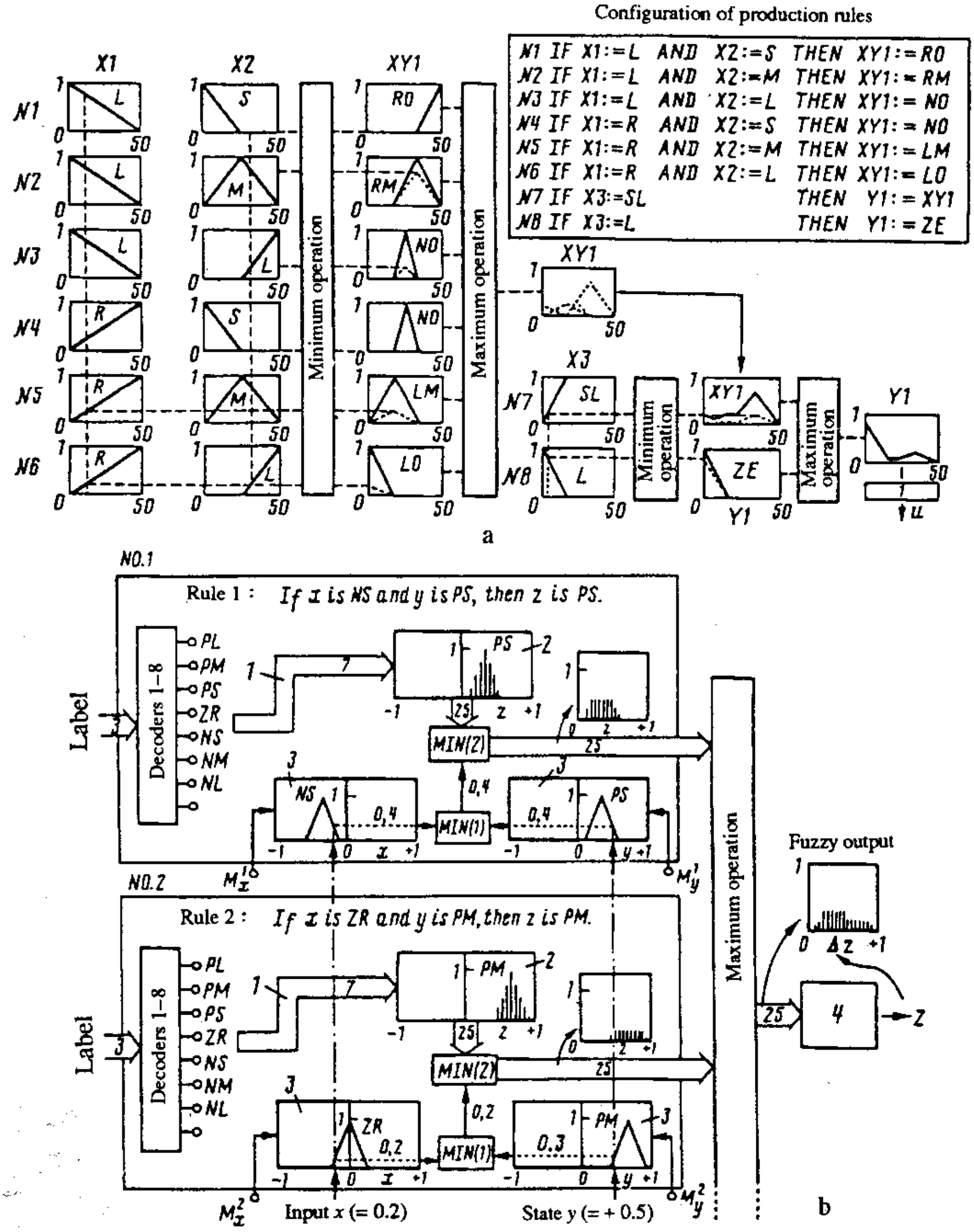
Between 10 (analog chip) and 16 (digital chip) logic rules can be implemented on these chips [3]. The use of parallel reasoning by means of neural nets can be employed to improve substantially the utility of fuzzy processors as embedded printed circuit boards for a wide range of industrial automatic control systems [68–70]. In this case, the number of rules per chip may reach 117 to 256 rules (depending on the manufacturing technology), which is significant for designing intelligent automatic control systems and fuzzy logic expert systems.

A new fuzzy logic processor utilizing quantum effects (in the form of controllable quantum Josephson junctions) has been developed in [71]. This processor realizes 60 logic rules, processes four variables in 300 μs (implying a logic execution speed of 2×10^9 logic rules per second) and combines digital and analog technology. A description of other projects to develop fuzzy processor models and their features is given in [2, 3, 10, 72].

The most popular tool designs for hardware and software support of fuzzy controllers and control systems include the FRUITAX (Fuzzy RUle Information Processing Tool for Advanced Control Systems), the LINK man expert system for image processing control, the FLS computerized interactive supervisory management system, and the IFCS (Integrated Fuzzy Control Design System) together with the RPX-FUZZY, FS-2000, etc., software design systems [72, 73]. A series of fuzzy controllers and FZ-1000 type control systems have been developed on the basis of these tools, including FZ-5000, MICREX-F 250, MICREX-F 500, FOC-2001, FOC-2001A, FOC-2001AH, EX-100, EX-1000, EX-1000/32, EX-FUZZY, HX-1000, TDCS 3000 LCN and many others [2, 25, 26]. The design principles and features of such fuzzy control systems are examined in the third and fourth sections of this paper.

Figure 3 shows a sample architecture of an Omron FZ-3000/3010 universal fuzzy controller used in numerical program control sets [74, 75]; a MICREX-500 fuzzy controller design by Fuji Electric used in crane automatic control systems is shown in Fig. 4 [76]. Both controllers employ the FRUITAX tools.

Workstation for the computer-aided design (CAD) of fuzzy processors have been developed for such fuzzy controllers (the CAD became operational in February 1989 [77, 78]). Software combined with a specially developed fuzzy processor memory structure are used in this case. The CAD system employs a generalized fuzzy logic reasoning rule and a method for selecting defuzzifier statements (for selecting the nonfuzzy specific value of the control functions). The logic speed ranges from 6 to 100 million rules per second, with an unlimited number of rules on the chips. A workstation [79] has been developed to design fuzzy controllers for consumer electronics. This workstation can be used to design real-time fuzzy controllers, to generate fuzzy knowledge bases, and for self-training by simulation on a personal computer utilizing the MS-DOS operating system. The FZY-LIB applied program library and the FZY-EDP graphics editor developed in [80] can



Configuration of production rules

N1 IF X1:=L AND X2:=S THEN XY1:=RO
N2 IF X1:=L AND X2:=M THEN XY1:=RM
N3 IF X1:=L AND X2:=L THEN XY1:=NO
N4 IF X1:=R AND X2:=S THEN XY1:=NO
N5 IF X1:=R AND X2:=M THEN XY1:=LM
N6 IF X1:=R AND X2:=L THEN XY1:=LO
N7 IF X3:=SL THEN Y1:=XY1
N8 IF X3:=L THEN Y1:=ZE

Rule 1 : If x is NS and y is PS, then z is PS.

Rule 2 : If x is ZR and y is PM, then z is PM.

Fig. 2. Block diagram of a fuzzy controller: a) the center of gravity fuzzy logic circuit: *L*, *R*, sL, *M*, *S*, RO, RM, NO, LM, ZE—the "*left*," "*right*," "*small left*," "*mean*," "*small mean*," etc., linguistic variables; 1) Defuzzifier; *u*) the nonfuzzy control value. b) The structure of a fuzzy controller with hard-wired fuzzy logic; 1) sampling bus; 2) membership function generator; 3) membership function circuit; 4) defuzzifier; *z*) controller output signal (the nonfuzzy control output signal values); NS, PS, PM, ZR—the "*negative small*," "*positive small*," "*positive mean*," etc., linguistic variables.

be used to interact with control objects with 17 input signals and two output signals in an interactive control mode; a composition (max-min) fuzzy logic rule is program-implemented on a PC XT/AT personal computer. The IFCS comprehensive design system [81, 82] is designed to develop real-time AS3000 and J3100 hierarchical fuzzy control systems containing nonfuzzy controllers on the lower data acquisition and processing level. The FCSS [83] and FUZZY CAD [84] design tools are employed to design fuzzy controllers utilizing expert systems and for modeling dynamic systems of variable structure.

Thus, the CAD workstations can be used to construct logic controllers that are in turn based on VLSI fuzzy processors. In this case, the controllers are superior to traditional P, PI, and PID controllers in terms of the quality of the transients and the achievement of control goals.

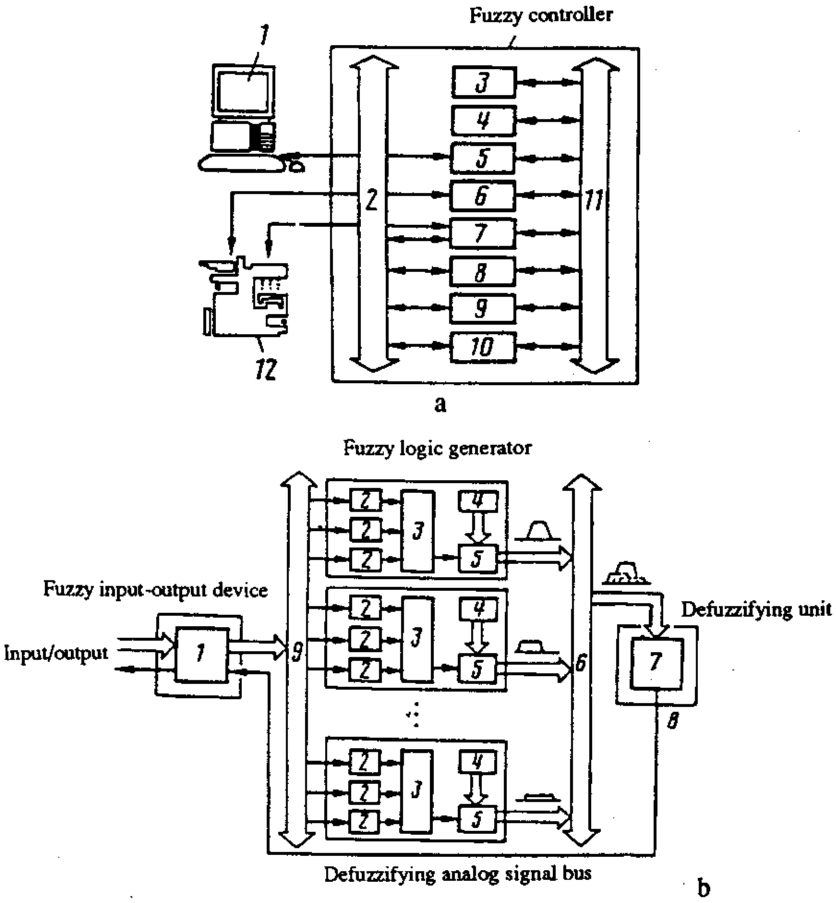


Fig. 3. Fuzzy controller: a) fuzzy controller structure: 1) external personal computer-based peripheral computer; 2) analog bus for high-speed data transmission; 3) arithmetic logic device; 4) memory; 5) interface; 6) digital input-output device; 7) fuzzy input-output device; 8) defuzzifier (selection of nonfuzzy value); 9, 10) nonfuzzy logic unit; 11) common digital signal transmission bus; 12) numerical program control sets. b) Fuzzy logic circuit in fuzzy controller: 1) input-output signal sampler; 2) membership function of logic packet signal; 3) circuit generating the min values of the membership functions of the logic packet signal; 4) generator of logic membership function; 5) circuit generating min values of the logic membership functions; 6) circuit generating the max values of the logic membership functions; 7) defuzzifier circuit; 8) center of gravity logic signal; 9) input analog signal bus.

3. Examples of Fuzzy Models of Logic Controllers and Commercial Automatic Control Systems

In this section we will provide as illustrations specific examples of fuzzy controller and industrial automatic control systems of independent interest in this field.

Examples of fuzzy models of multipurpose industrial automatic control systems. The hardware implementation of microprocessor fuzzy controllers shown in Fig. 1 have found successful application in industrial fuzzy automatic control systems [1, 85–87].

The structure of the fuzzy control system [85] used for the management and control of a water treatment facility (Fig. 6) is shown in Fig. 5.

The CENTUM-XL integrated universal automatic control system was developed in [86]. Figure 7 shows the hardware/software structure of such a system for an industrial profile paper manufacturing and testing system on the paper machine shown schematically in Fig. 8.

The use of a CENTUM-XL type fuzzy automatic control system to monitor and control waste-free industrial by-product and municipal refuse incineration in a refuse furnace, as shown in Fig. 9, has shown satisfactory results.

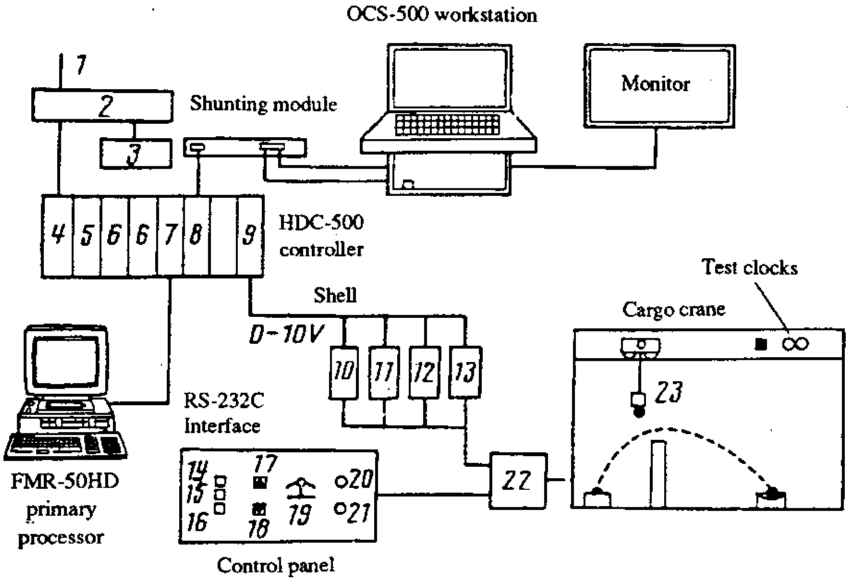


Fig. 4. The MICREX fuzzy controller: 1) 100 V ac power supply; 2) power bus module; 3) backup power supply; 4) controller power supply; 5) function keyboard for common control bus; 6) main processor keyboard; 7) interface keyboard; 8) interface control network keyboard; 9) ring interface network module; 10) analog input module; 11) analog output module; 12) digital input module; 13) digital output module; 14) automatic control button; 15) manual control button; 16) return button; 17) vertical motion button; 18) horizontal motion button; 19) control lever; 20) start button; 21) stop button; 22) controller; 23) electromagnet.

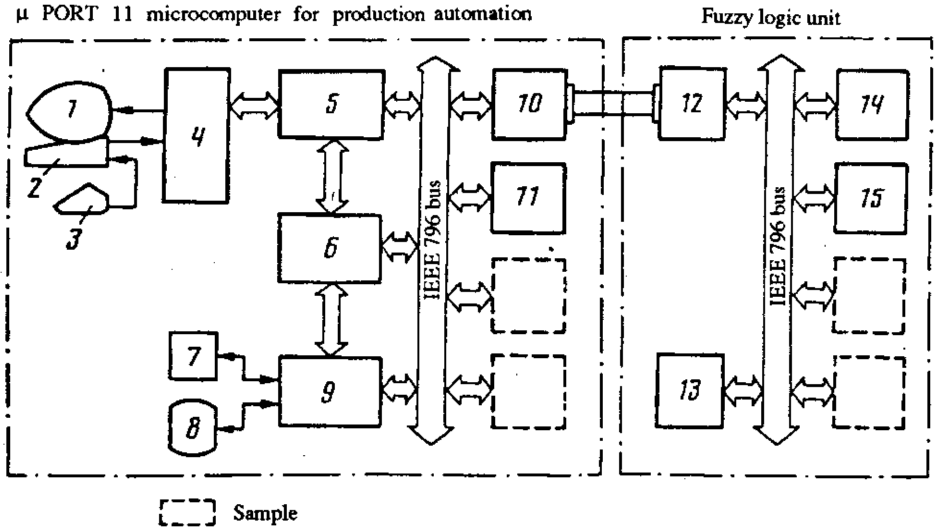


Fig. 5. Block diagram of fuzzy control system: 1) display; 2) keyboard; 3) mouse; 4) graphics processor; 5) main processor; 6) multiport memory; 7) floppy disk memory; 8) hard disk memory; 9) file processor; 10, 12) data transmission bus coupling channel; 11) common memory; 13) terminal; 14) fuzzy processor; 15) local memory.

The control and decision-making unit in such intelligent systems is implemented by means of fuzzy structure models and control algorithms, as well as generalized fuzzy production logic rules, advanced description forms, and deep knowledge representation in expert systems. We will now briefly examine sample applications of fuzzy models of knowledge-based logic controllers used in intelligent industrial automatic control systems in various problem-oriented domains. A qualitative description of the application of fuzzy automatic control system models is based on examples of fuzzy logic controllers widely used in the development of automated industrial process control systems, flexible manufacturing systems, robotic complexes, control systems for complex dynamic systems, etc. A comparison with traditional systems in control theory makes it possible to demonstrate the noticeable features and advantages of employing fuzzy controllers in industrial automatic control systems.

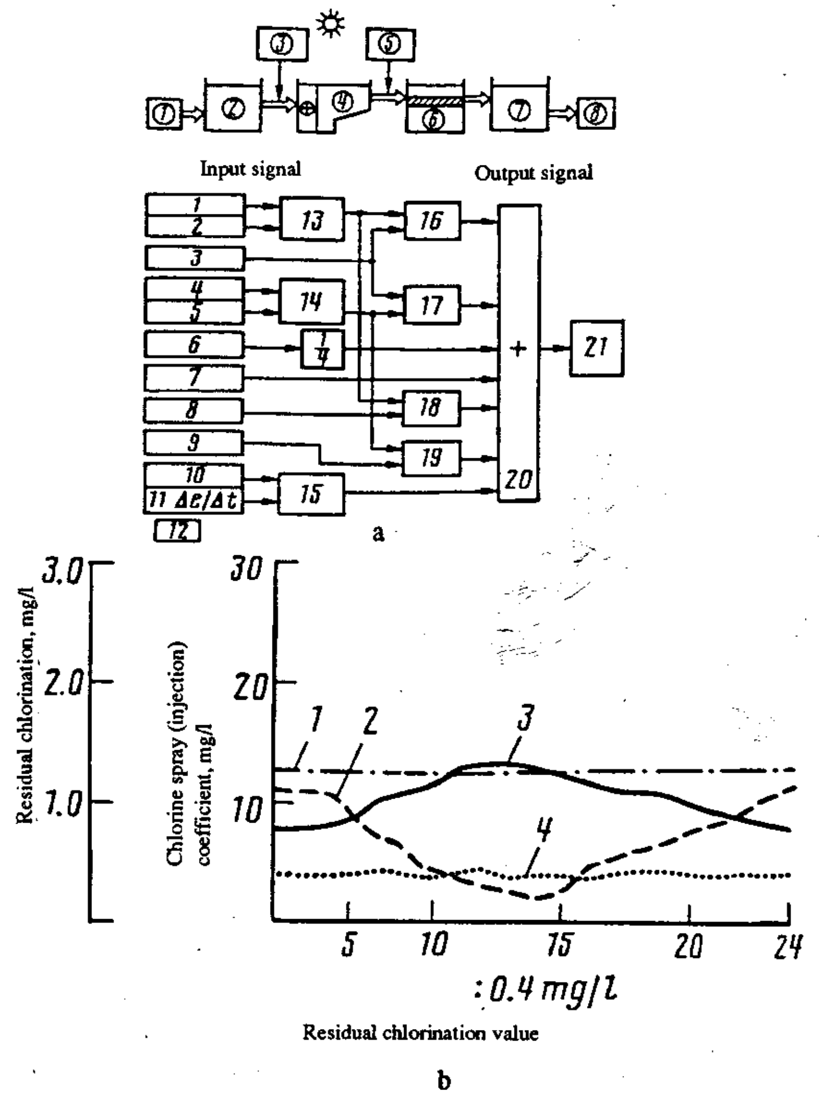


Fig. 6. Fuzzy control system for water treatment facility: a) block diagram of water treatment facility and acquisition of test parameters; 1) water source; 2) water inlet; 3) water chlorination batcher input; 4) settlement tank; 5) residual chlorination unit; 6) filtering basin; 7) water treatment reservoir; 8) water supply network; 1) weather prediction block; 2, 3) average water temperature prediction block; 4) organic water composition prediction block; 5) water inorganic compound content prediction block; 6) activated coal additive formation block; 7) supplementary chemical water processing block; 8) block for estimating current changes in weather; 9) real-time chlorine batcher; 10) block for estimating changes in residual water chlorination; 12) manual data input unit to blocks 1–9 (covering status of the water source) and to blocks 10-12 (for automatic data input); 13) water insulation estimation block; 14) water chlorination batching block; 15, 18, 19) additive batcher spray correction blocks; 16) meteorological data correction block; 17) main water parameter correction block; 20) logic adder block; 21) chlorinated water injection block (ml/l). b) Results from application of a fuzzy automatic control system for selecting water chlorination concentration: 1) manual control of the chlorine dose injection factor; 2) manual control of residual chlorination doses; 3) fuzzy algorithm for controlling chlorine spray dose factor; 4) fuzzy algorithm for controlling residual chlorination doses. The consumption rate of the chlorine spray dose from traditional control was 478 l/day, and from the fuzzy control algorithm was 459 l/day.

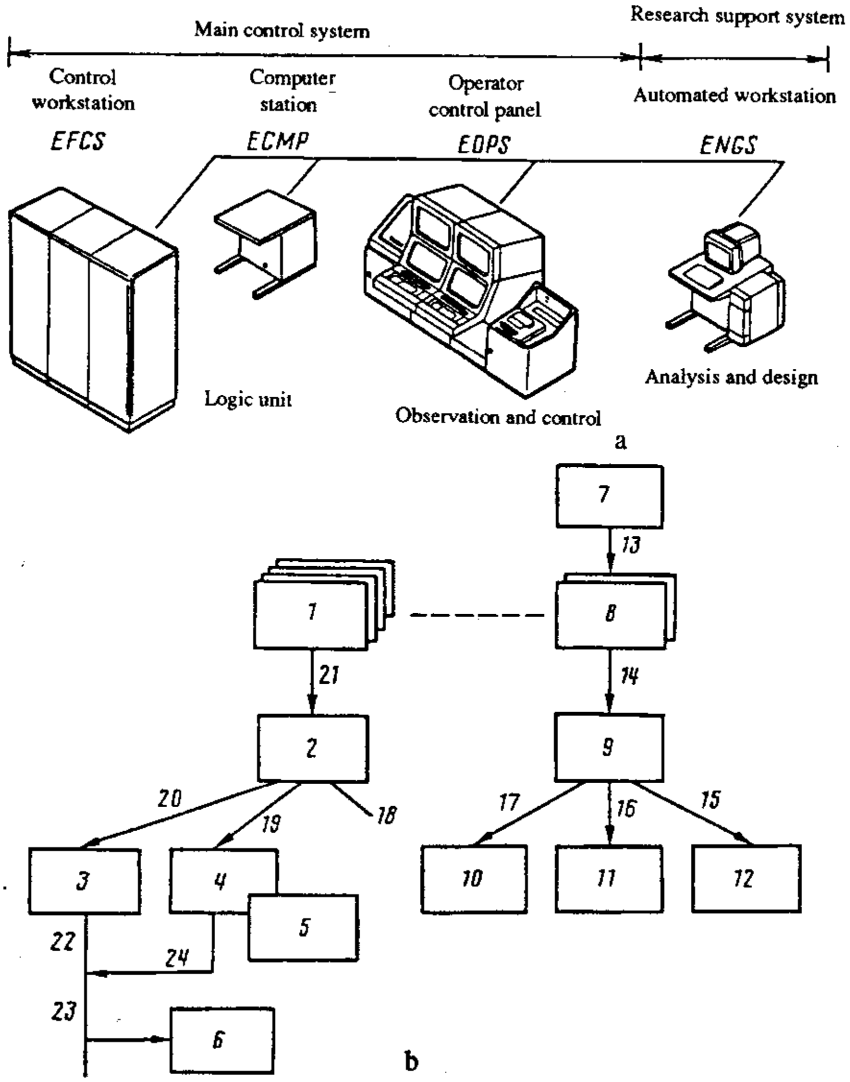


Fig. 7. The CENTUM-XL fuzzy automatic control system: a) Structure of the fuzzy automatic control system. b) Software structure: 1) fuzzy software menu; 2) menu of knowledge base of artificial intelligence system; 3, 4) knowledge base windows mode; 5) knowledge base menu; 6) windows block for group selection of supervisor management; 7) windows mode for fuzzy control algorithm; 8) fuzzy control menu; 9) menu for choosing logic reasoning conditions; 10) windows mode for displaying logic conditions; 11) windows mode for adaptive control; 12) windows mode for the present logic decision-making rule; 13) selection of maximum of membership functions; 14) selection of logic output; 15) present logic rule; 16) adaptation conditions; 17) display of logic conclusion; 18) exclusion; 19) correction; 20) supplementary addition to knowledge base; 21) problem-oriented knowledge base; 22) group input to knowledge base; 23) limited sample; 24) sample from knowledge base.

The application of fuzzy automatic control systems in problem-oriented domains. The development of universal fuzzy controller structures has led to the wide application of fuzzy controllers and intelligent automatic control systems in various fields [2, 25, 26]. As noted previously, among the first industrial prototypes of fuzzy automatic control systems were the control systems employed at a cement factory, on metro trains, and the on-board control system for the Shuttle spacecraft.

In the latter case, flight was simulated for a 1-h period, while the unit was located 100 m from the main station. It was necessary to maintain the orientation of the control object in Earth orbit. The structure of the fuzzy controller employed to control the orientation of an artificial satellite was developed in [88, 89]. Figure 10 shows an overall view of the spacecraft, a block diagram of the fuzzy controller, and the results of simulating a fuzzy controller as a multilevel delay relay [88, 89].

A comparison of the results of modeling a fuzzy controller with a traditional controller under deviation control feedback showed good results for the fuzzy controller within the automatic control system. In this case, the fuzzy controller parameters were chosen based on Lyapunov stability, which enabled a robust fuzzy controller to be obtained in the parameter space for a given critical thrust control to correct spacecraft position.

An overall view of a fuzzy controller and results from the simulation of the motion control of a metropolitan train [90] are shown in Fig. 11. The advantages in terms of the train stopping accuracy, continuous motion (acceleration and stopping), travel comfort, and power savings were achieved by means of a fuzzy controller, a data acquisition system (Fig. 11a) based on ultrasonic sensors and information processing based on fuzzy algorithms [90–92]. The system consists of hardware and software tools for simulating and predicting the metropolitan electric train control mode and control command generation mode in real time. The fuzzy logic process is executed by means of a knowledge base comprised of a factual base and a logic (production) rule base. The results from the incorporation and operation (for a five-year period) of the system from the viewpoint of train stopping position accuracy were evaluated in [93]. The accuracy was estimated on the basis of experimental data obtained from 11,395 stopping position measurements. The system yielded a stop position processing accuracy of ± 5 cm in more than 4500 cases; the average accuracy was 3.57 cm.

The application of a fuzzy automatic control system in ventilation control applications [94, 95] in large-scale motor vehicle tunnels on high-speed routes is illustrated in Fig. 12. It is clear from Fig. 12d that the fuzzy automatic control system made it possible to increase the capacity of the tunnel, reduced carbon monoxide concentrations in the tunnel from vehicle exhaust, and required 2.5 times fewer fans between 5 am and 4 pm.

A sample application of a fuzzy controller in artificial lungs (AL) [96] is shown in Fig. 13. This class of devices makes it possible to implement so-called benign AL conditions for patient rehabilitation and treatment [97, 98]. In view of

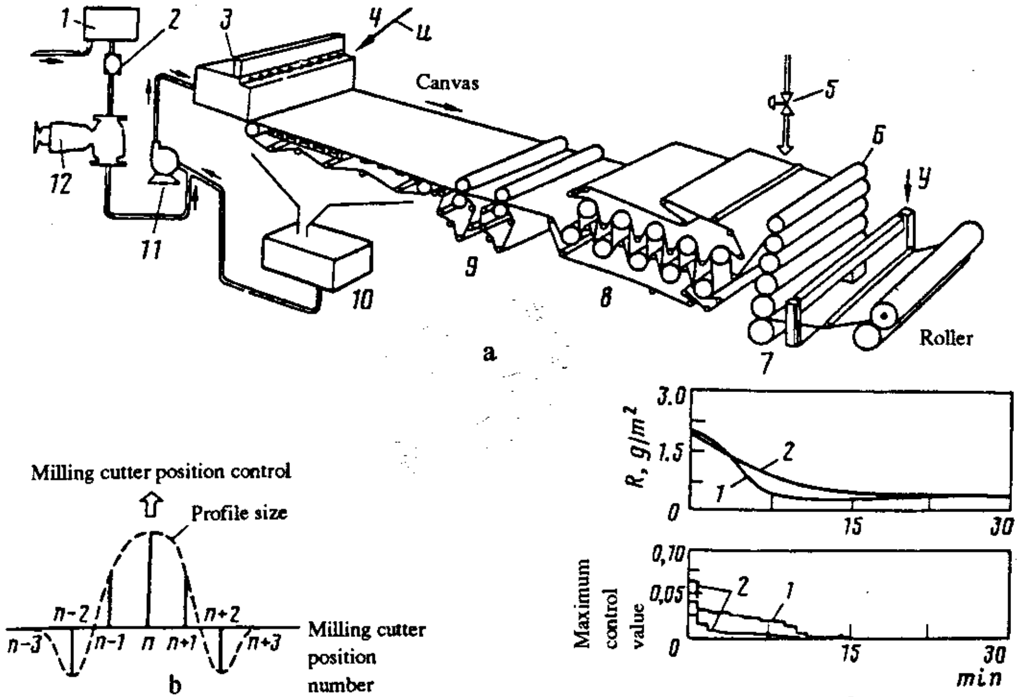
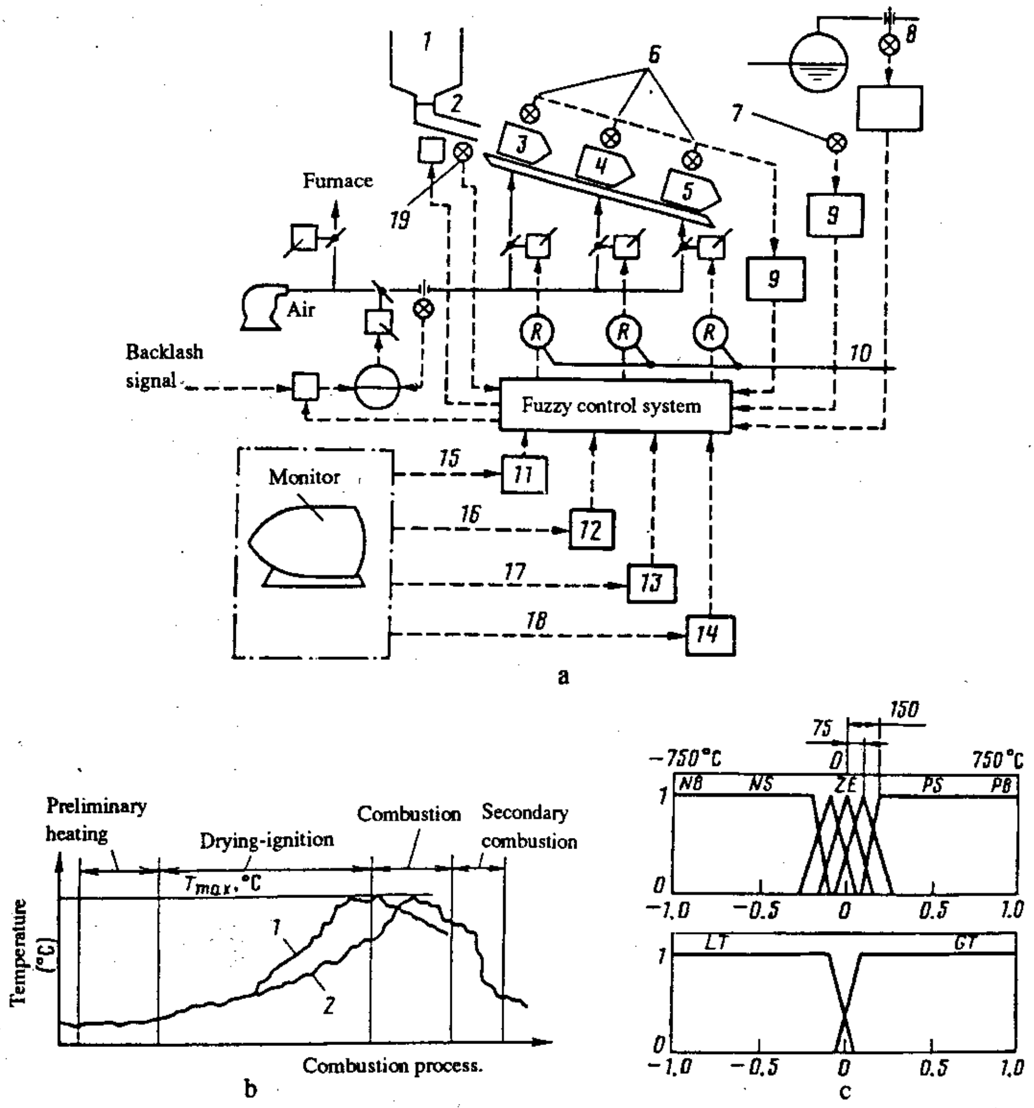
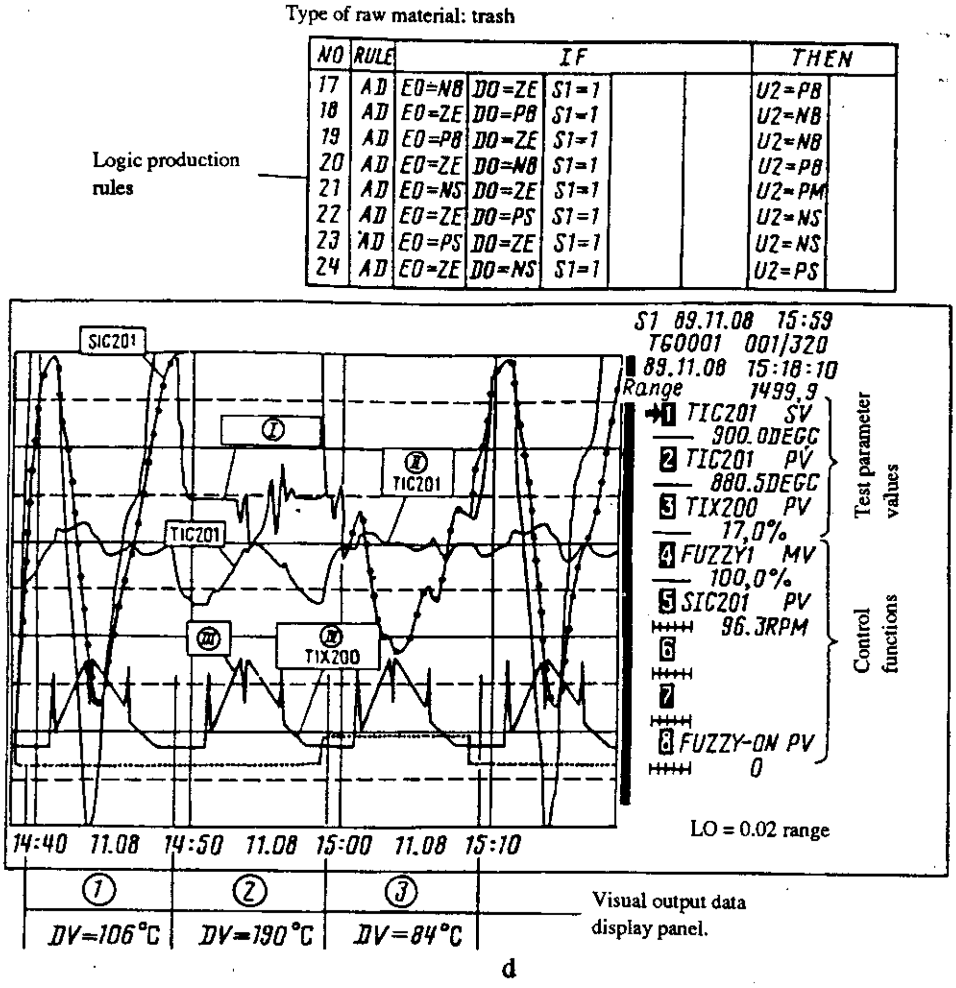


Fig. 8. Structure of paper machine: a) Industrial paper manufacturing and profiling process: 1) raw material storage vessel; 2) electromagnetic flowmeter; 3) feed box; 4) opener for regulated clutch section; 5) vapor feed valve; 6) calendar; 7) conditioning air feed sensor; 8) dryer; 9) presser; 10) return water vessel; 11) load pump; 12) standard flow valve; *u*) clutch control section closure signal; *y*) profile sensor. b) Type of test signal and control over paper profile milling cutter. c) Results of the application of fuzzy control to compensate initial perturbations in paper tension (the difference between the change in the minimum and maximum values of R) and the maximum control signal amplitudes for monitoring paper tension; 1) fuzzy control; 2) program control.

the importance of this example to the theory of fuzzy models of dynamic control systems, we will consider some of its methodological features.

Formation of feedback in control system structures based on fuzzy controllers. The actuator mechanism (decision-making mechanism) in ALs and the final result are monitored on the basis of two logic-dynamic feedback loops: the physiological loop of the external respiratory system (ERS) and the AL loop [96, 98]. The physiological mechanism of interaction between these logic-dynamic loops (feedback loops) of the ERS and AL is described in detail in [96, 98] and implements the protective negative responses of the natural body to the effect of the artificial lungs. The interaction of the regulatory neuroendocritical centers of the ERS of the patient's body and the operator controls of the AL implements dual control [99]. Operator functions in this case are performed by a fuzzy controller that simulates operator activities based on a coarse model of the control object and expert evaluations. The purpose of dual control is to distribute the control actions between the artificial lung apparatus and the external respiration regulation system. In this case, the homeostasis of the natural body through the feedback loops of the ERS orients the body to the controls of the AL through an information parameter set represented as the ratio (f_h/f) of the heart contraction frequency (HCF) f_h to the respiration frequency f. It is established that the ratio (f_h/f) acceptable to the human body is approximately 4. If the respiration frequency f is regulated, and the HCF is recorded, we obtain a model of noninvasive control. In this case, the discrete states (f_h/f) on the ERS channels correspond to the present analog states on the AL channel. This produces a certain dual control redundancy (from the interaction of two antagonistic ERS and AL control mechanisms). A formalization of the description of feedback interacting





Type of raw material: trash

NO	RULE	IF					THEN	
17	AD	E0≐NB	D0=ZE	S1=1			U2=PB	
18	AD	E0=ZE	D0=PB	S1=1			U2=NB	
19	AD	E0=PB	D0=ZE	S1=1			U2=NB	
20	AD	E0=ZE	D0=NB	S1=1			U2=PB	
21	AD	E0=NS	D0=ZE	S1=1			U2=PM	
22	AD	E0=ZE	D0=PS	S1=1			U2=NS	
23	AD	E0=PS	D0=ZE	S1=1			U2=NS	
24	AD	E0=ZE	D0=NS	S1=1			U2=PS	

Fig. 9. Fuzzy control system for controlling a garbage and industrial waste incineration process: a) Block diagram of refuse destruction process: 1) loading chute; 2) injector; 3) dryer; 4) combustion; 5) secondary combustion; 6) temperature sensor; 7) gas injection for temperature control in furnace; 8) standard signal set unit; 9, 11–14) membership function; 10) ratio/coefficient setting; 15) operator setting of parameters; 16) calorific value; 17) quantitative estimate of moisture content; 18) specific volume; 19) load rate sensor. b) Change in temperature during combustion: 1) relative moisture content; 2) normative value. c) Type of membership functions: NB, NS, ZE, PS, LT, PB, GT) the "negative big," "negative small," "zero," "positively small," etc., linguistic variables. d) Type of production rules and control results based on fuzzy PI-controller: I) fuzzy output; II) furnace temperature; III) function disruption; IV) calorie fluctuations; 1) sample values of refuse incineration process under PI-controller control; 2) sample values for a PI-controller for the case of unprocessed refuse; 3) a fuzzy controller for combustion of untreated refuse.

through the redundant logic-dynamic channels makes it necessary to employ a variety of nonclassical logic. Thus a fuzzy controller (FC in Fig. 13a) in the feedback channel is considered within a class of linguistic approximations based on classical fuzzy logic, whereas the logic behavior of the second ERS channel (which realizes the negative responses of the natural body) obeys material implication laws of quantum fuzzy logic [96, 100]. Thus, the compensatory responses of the respiratory hemostat (the second feedback channel) are in the general case described within the framework of models of quantum fuzzy logic. In this case, consistent with the modeling results in [101, 102], the material implication of quantum logic is characterized by the most rigorous logical reasoning in the class of multivalued (fuzzy) logic, contains more information and is less sensitive to variations in raw data compared to classical versions.

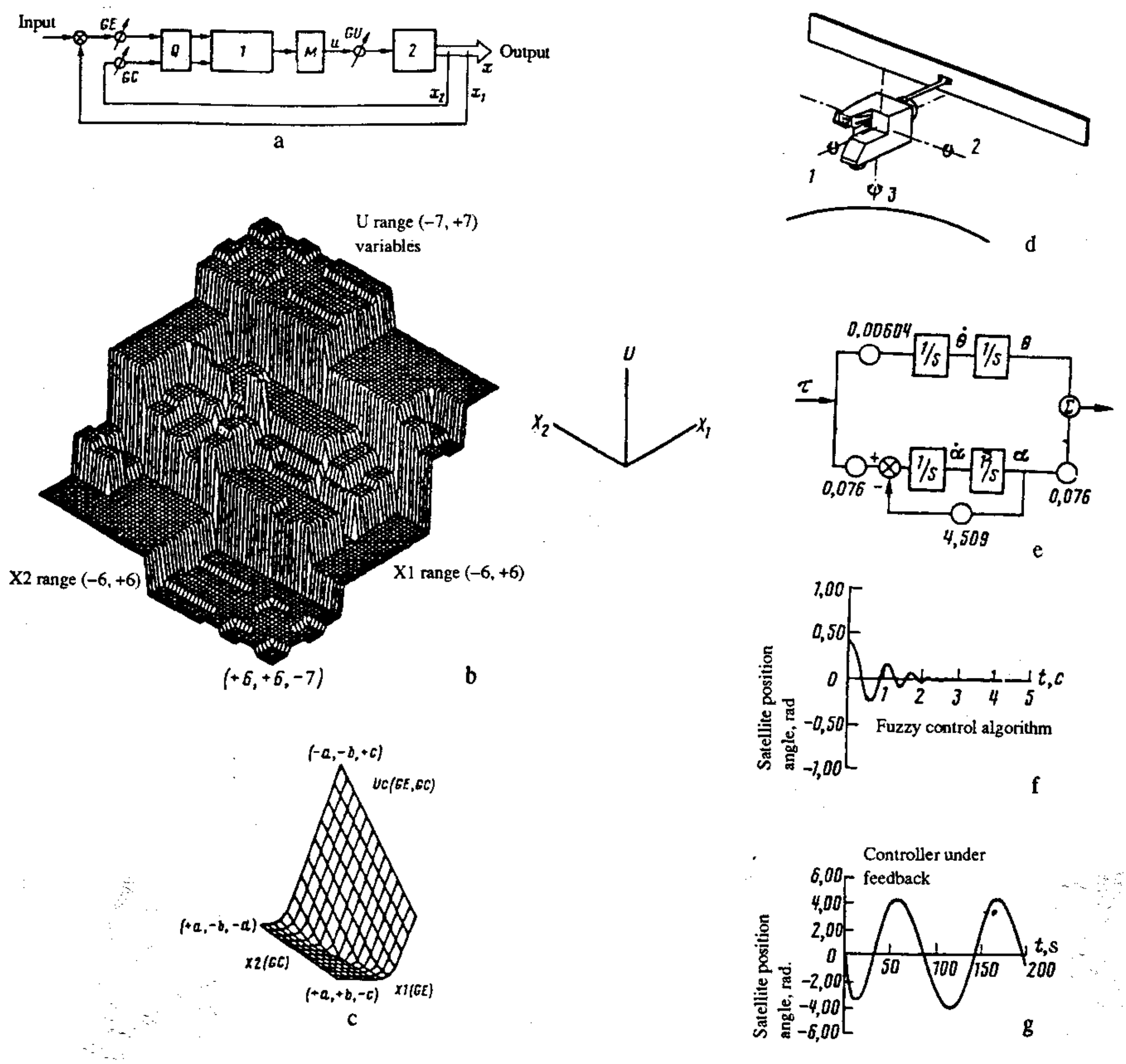


Fig. 10. A fuzzy automatic control system for an artificial satellite: a) Block diagram of the fuzzy controller: 1) production rules for knowledge-based process control; 2) process as a control object (E is the error; C is the rate of change of the error). b) Simulation of a fuzzy controller as a multilevel delay relay. c) The critical surface in terms of thrust. d) Overall view of the artificial satellite: 1) pitch angle axis; 2) spacecraft motion along the roll axis; 3) yaw angle oriented to the center of the Earth. e) Satellite control loop. f, g) Result from modeling the position angle (orientation) of the satellite.

In the general case, such feedback is generated in complex systems by means of linguistic approximations of control loops and fuzzy controllers utilizing a two-channel invariance principle [2, 17]. In this case, the first deviation control channel with error composition utilizes a fuzzy controller based on classical fuzzy logic; the second generalized control channel and the system state channel is designed to take into account changes in interrelated information state parameters of the object under extremal cases and utilizes a fuzzy intelligent controller whose logic output is implemented in terms of quantum (nondistributive) fuzzy logic [100]. An example of this case is an intelligent automatic control system for the AL apparatus shown in Fig. 13. The respiratory loop of the artificial lung is controlled by means of a fuzzy controller based on classical fuzzy logic; a fuzzy quantum logic controller monitors the interaction of the respiratory loop and the discrete states

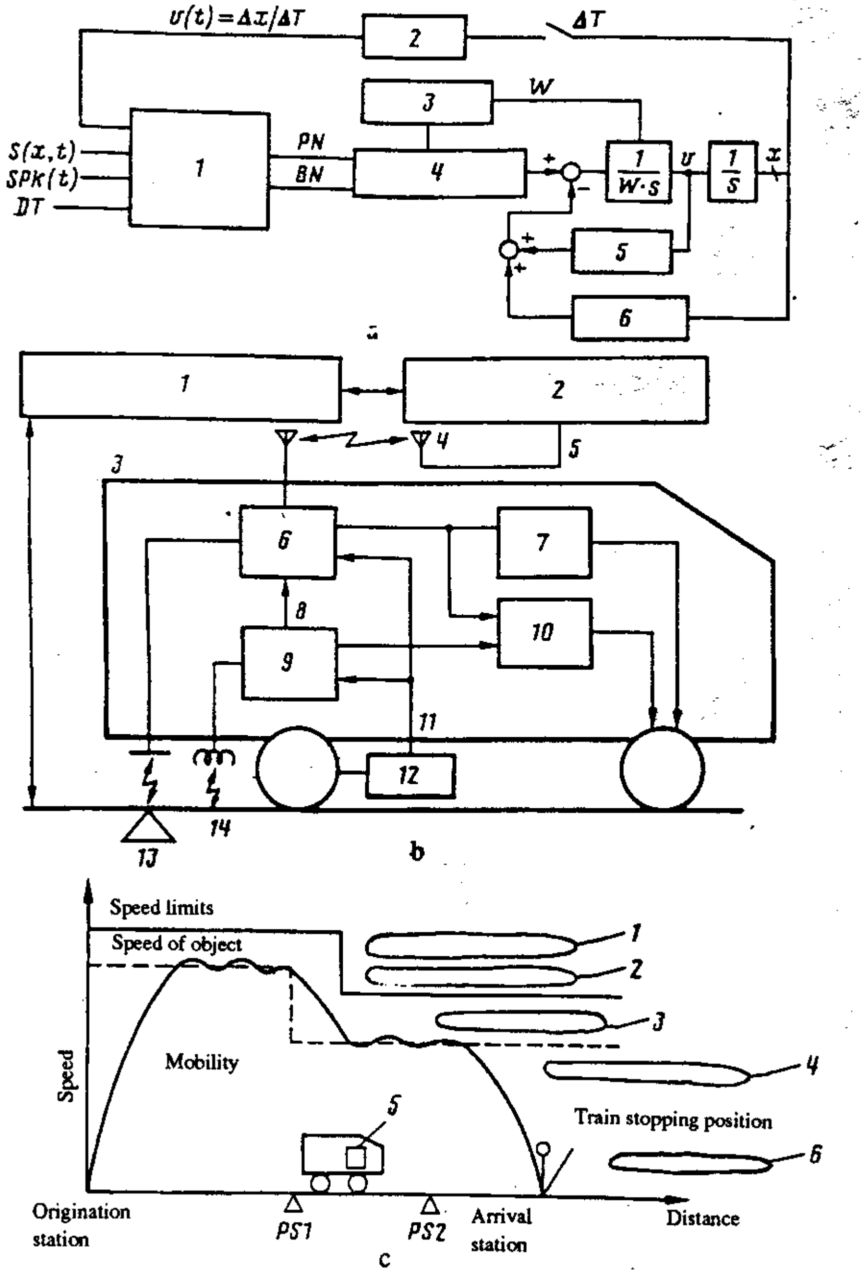


Fig. 11. Fuzzy automatic control system for a metropolitan train: a) Fuzzy controller: 1) ATO fuzzy controller; 2) speed sensor; 3) load modification device; 4) thrust and braking controller; 5) stability of present position; 6) characterization and change in overall stability. Notation: t is the time, v is the speed, x is the distance, S is the supervisory simulator control signal, P is the power marker, N is the braking marker, S_{pk} is the sampling signal, and T is the train time. b) Overall view of controller: 1) automated simulator (ATS); 2) supervisory simulator training system (ATS); 3, 4) simulator and signalling sensors; 5) supervisory control signal; 6) ATO control system panel; 7) thrust controller; 8) signal to train engineer cabin; 9) ATS system control panel; 10) train braking controller; 11) distance signal pulse burst; 12) tachometer generator; 13) position marker; 14) path recording circuit. c) Results of a simulation of the train motion: PS1, PS2) braking start and finish markers; o) designation of the operating characteristics and efficiency factors of the system; 1) time in motion; 2) power consumption; 3) reliability; 4) comfort; 5) fuzzy control system; 6) stopping zone.

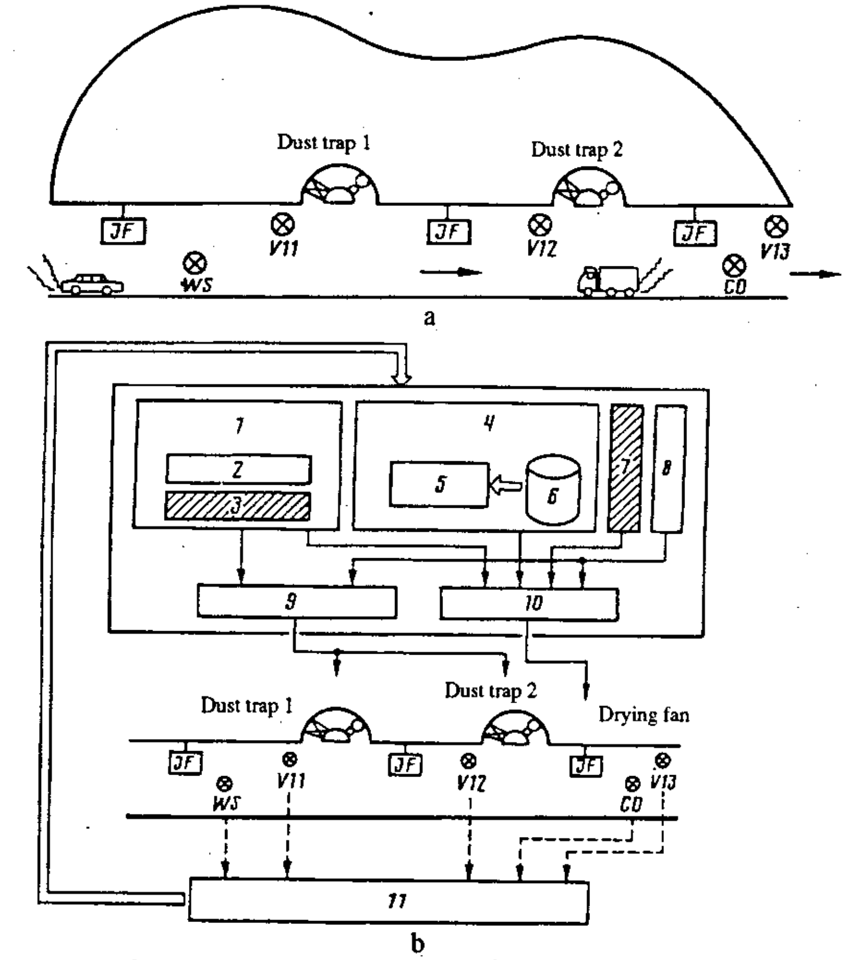
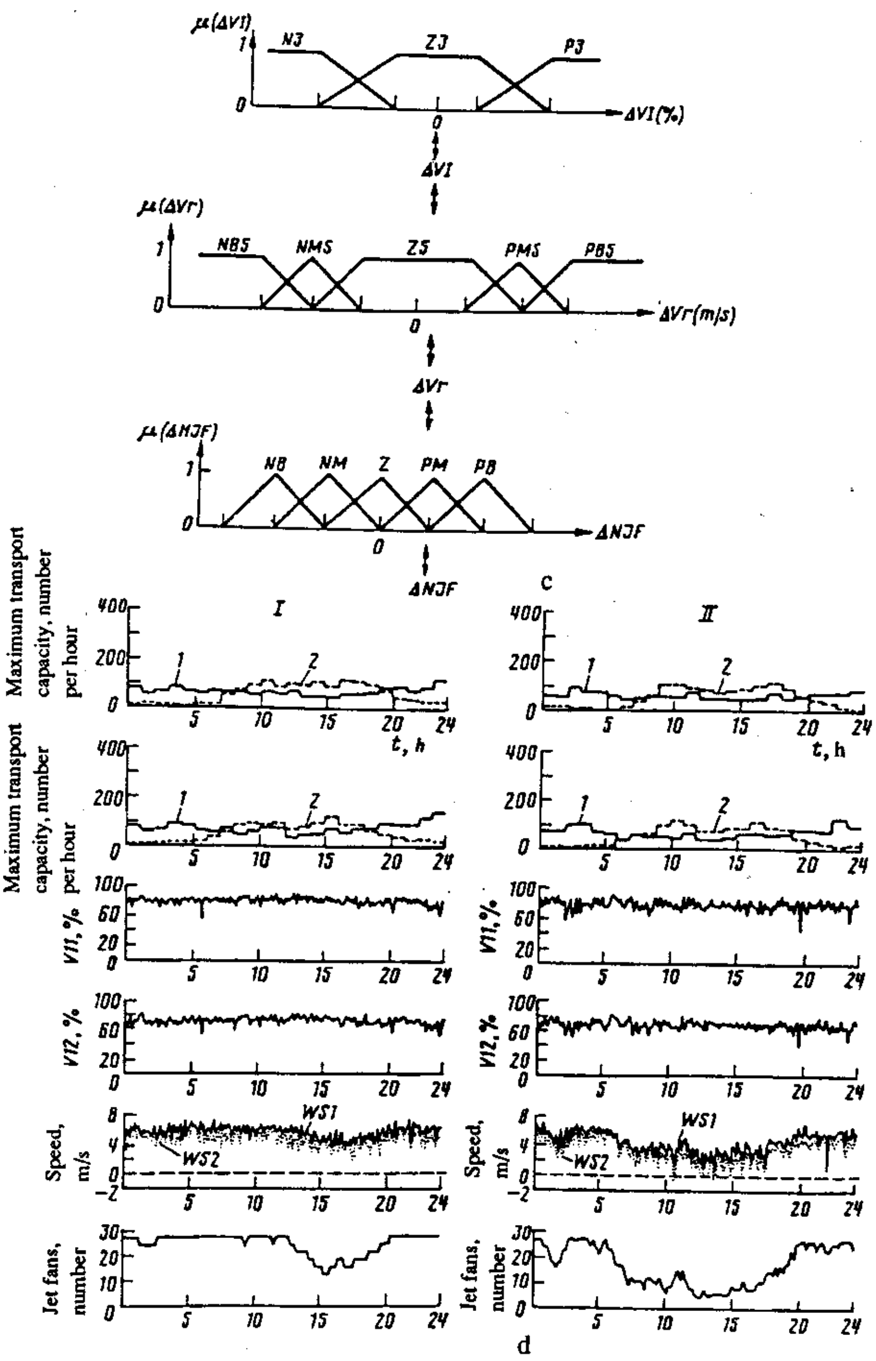


Fig. 12. A fuzzy automatic control system for roadway tunnel fans: a) Overall view of fans and measurement-test instrumentation. Notation: *V11 – V13*) smog infiltration sensors; CO) carbon monoxide densitometer; WS) anemoscope and anemometer; JF) jet fan; →) wind direction in tunnel. b) Block diagram of fuzzy automatic control system: 1) fan control domain; 2) numerical parameters (NJF); 3) functional parameters; 4) fan set feedback control; 5) fuzzy control; 6) production control logic rules; 7) level control; 8) emergency control; 9) block for determining flow force and the number of dust traps; 10) determination of the required number of operating jet fans; 11) sensors (smog level, carbon dioxide, tunnel flow). Note: the shaded blocks denote the use of artificial intelligence. c) The membership functions: N3, Z3, P3, NB5, NM5, Z5, PM5, PB5, NB, NM, Z, PM, PB—denoting "*negative*," "*zero*," "*positive*," "*very negative*," "*very positive*," "*near positive*," etc. linguistic variables. d) Results of the application of the fuzzy automatic control system: 1) maximum value; 2) minimum value; I) results of measurement of test parameters without employing fuzzy control; II) results of measurement of control parameters employing a fuzzy control algorithm.

of the cardiovascular system in the form of the HCF (which is in an antagonistic relation to the respiratory system) and corrects the corresponding tables of linguistic decision-making rules to achieve invariance of the dynamic behavior of the control system. In this case, the compensatory capabilities of homeostasis of the integral mechanism are taken into account.

Another example of generating control loops for a complex robotics system is the approach developed in [103] based on cognitive graphics to describe and predict the development of dynamic scenarios in extremal cases. Such an approach makes it possible to develop a fuzzy intelligent controller knowledge base and to plan routes of an independent mobile robot in extremal cases. The structures of mobile industrial robot systems (under fuzzy logic remote control) with a vertically traveling robot are described in [104]: for application to cleaning horizontal (including ceilings) and vertical surfaces, for cutting metal surfaces and other industrial operations [105]. The results of modeling the orientation and motion of the



independent module (the robot group control model) under conditions of obstacles using cognitive graphics [103, 106] and its experimental operation demonstrated the effectiveness of employing fuzzy control algorithms in mobile remote controlled robotic systems employed under extreme and emergency conditions [104, 105].

CONCLUSION

The experimental operation of fuzzy controllers and intelligent automatic control systems has been based on a number of additional controls developed by a variety of foreign companies [107]:

—air traffic and aircraft landing control;

—monitoring of reactor parameters in a nuclear power plant as well as hydroelectric and electric generation stations;

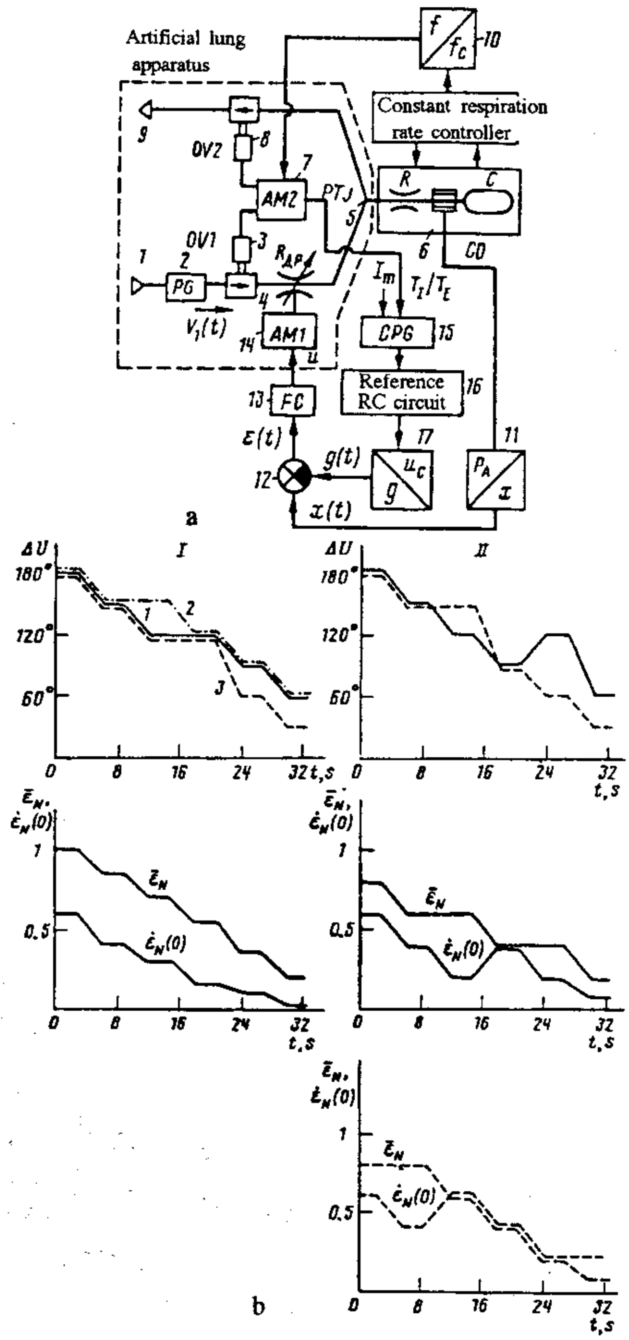


Fig. 13. Fuzzy controller for artificial lung apparatus (AL): a) Block diagram of dual control over AL process: 1) air collector; 2) pressure generator (PG); 3) air valve (electromagnetic valve); 4) control choke; 5) patient T-joint (PTJ); 6) control object (CO) (lungs); 7) valve actuator mechanism (AM) and current pulse generator (CPG); 8) output valve (OV) (electromagnetic valve); 9) air bleed; 10) converter of the heart contraction rate (HCF) into respiratory rate (RR); 11) converter of P_A into a control quantity; 12) adder; 13) fuzzy controller (FC); 14) actuator mechanism (AM) (step motor); 15) current pulse generator (CPG); 16) reference RC network; 17) converter of u_s into an actuator control. b) Results of modeling fuzzy controller control: I) estimate of control sensitivity to changes in the parameters of the selected membership function (graph 1 corresponds to $K_1 = 2, K_2 = 0.3$; graph 2 corresponds to $K_1 = 2, K_2 = 1$; graph 3 corresponds to $K_1 = 1.5, K_2 = 0.3$); II) estimate of control sensitivity to changes in process trajectory (for $K_1 = 2, K_2 = 0.3$).

—control of mining machines;
—testing of water purification and hardness for domestic applications;
—automatic electronic weighing scales;
—temperature control and suspension detection in clean rooms for manufacturing electronic equipment and ethylene;
—nondestructive testing of surface roughness;
—selection and design of supports for bridges;
—break down diagnostics in machine engineering structures;
—speech signal recognition for speech input-output devices;
—photographic and video cameras and industrial vision systems for robots;
—gas temperature and coking control in annealing furnaces;
—monitoring of blood and arterial pressure for automatic injection of medication doses;
—creation of classical and jazz musical compositions, etc.

The practical realization of specific fuzzy controllers and intelligent automatic control systems has had a detectable economic savings effect [2, 3, 25-29], and has considerably enriched and stimulated further theoretical research in the development of fuzzy control systems, diagnostics, and the monitoring of complex dynamic systems.

The wide variety of methods employed to develop knowledge bases and models of fuzzy industrial intelligent controllers and automatic control systems has made it necessary to develop a methodology and theoretical principles for the analysis, synthesis, and design of structures for such intelligent systems.

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